Matter Formed at the BNL Relativistic Heavy Ion Collider

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We suggest that the "new form of matter" found just above T_c by RHIC is made up of tightly bound quark-antiquark pairs, essentially 32 chirally restored (more precisely, nearly massless) mesons of the quantum numbers of π, σ, ρ and a_1. Taking the results of lattice gauge simulations (LGS) for the color Coulomb potential from the work of the Bielefeld group and feeding this into a relativistic two-body code, after modifying the heavy-quark lattice results so as to include the velocity-velocity interaction, all ground-state eigenvalues of the 32 mesons go to zero at T_c just as they do from below T_c as predicted by the vector manifestation (VM in short) of hidden local symmetry. This could explain the rapid rise in entropy up to T_c found in LGS calculations. We argue that how the dynamics work can be understood from the behavior of the hard and soft glue.

Introduction— Within a month or two of operation, RHIC found the "new matter" they formed to be an extremely strongly interacting liquid, nothing like the quark gluon plasma.

This brings up two issues: a long-standing "old" issue as to what the structure of the state is in the vicinity of, and below, the presumed chiral phase transition point and what the proper tool to understand it is and a "new" issue as to what lies above the critical point to which the accepted theory of strong interactions, QCD, is supposed to be able to access perturbatively. In this Letter, we wish to address these issues in terms of an old idea on in-medium hadron properties proposed in 1991 [1] which has been recently modernized with the powerful notion of "vector manifestation (VM)" of hidden local symmetry theory [2] and buttressed with results from lattice QCD. Our principal thesis of this paper is that just as it required an intricate and subtle mechanism to reach the VM structure of chiral symmetry just below T_c – which is yet far from fully understood – from the standard linear sigma model picture applicable (and established) at $T \sim 0$, the structure of matter infinitesimally above T_c could also be vastly intricate and subtle from the starting point of QCD at $T \sim \infty$ at which asymptotic freedom is applicable and "established." We will make here an admittedly leaping conjecture by extrapolating and inferring from available information coming from lattice results and hinted by RHIC data that the structures of matter just below and just above T_c could be related. Further arguments to support this conjecture will be presented in a later publication.

In this paper we shall focus on a new state of matter formed at high temperature probed by RHIC experiments, particularly in the vicinity of the critical temperature $T_c \sim 175$ MeV. We should mention that the question of how matter changes from one form of symmetry realization to another form of symmetry realization is a general and fundamental issue in physics and in the case of hadrons, this still remains a more or less open question. Our conclusion drawn based on a variety of arguments to be developed below will be that the transition is "con-

tinuous" across T_c in the sense that the same degrees of freedom that come up from below T_c are found just above T_c although perhaps in a disguised form.

As we will develop in this paper, the key to the possible new matter produced at RHIC and its connection to the matter below T_c is in the glue from the gluons exchanged between quarks and its role in Brown-Rho scaling.

Two types of glue— The first observation we make is that there are two types of glue, a soft one and a hard one (epoxy). This aspect has been emphasized recently in [3]. The fact that there are two glues was first found in the thesis work at Columbia by Yuefan Deng [4]. He found in lattice gauge simulations (LGS) that about half of the total glue, the soft glue, was melted as T reached T_c. The exchange of soft gluons holds hadrons together at temperatures below the phase transition temperature $T_c = 175\,MeV$. Below this temperature their coupling to hadrons produces a soft gluon condensate which is melted as T goes up to T_c. As the soft glue melts the constituent quarks turn into massless current quarks. The hard glue (epoxy) on the other hand begins to melt only above T_c. It is the epoxy condensate that produces the length parameter Λ_{QCD} by breaking scale invariance and through what is called "dimensional transmutation."

Brown-Rho scaling— In 1991 [1] Brown and Rho predicted using a dilaton field that as the soft glue melted with increasing temperature (or increasing density) hadron masses would decrease essentially proportional to the decrease in the soft gluon condensate, going to zero at T_c. Their scaling found in [1], $\frac{m^*}{m} \sim \frac{f_\pi^*}{f_\pi}$, can be related to the quark condensate,

$$\frac{m^*}{m} \sim \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \ . \tag{1}$$

Two recent independent studies in a generalized hidden local symmetry approach, one by Harada and Sasaki [5] and the other by Hidaka et al. [6], confirmed that both the vector and axial vector mesons go massless at the chiral restoration satisfying (1).

This so-called "Nambu scaling" was confirmed in heat

bath by Koch and Brown [7] from lattice results. Thermodynamics of quasiparticles; *i.e.*, that the entropy of a hadron with effective mass m^* can be obtained from that of mass m, simply replacing m by m^*, holds up. So entropy is just counting. The main correction to the early work is that the $T_c = 140\,MeV$ used there should be increased to $T_c = 175\,MeV$. The energy in the gluon condensate is therefore increased by $(140/175)^4 = 2.44$. This is important for the bag constant, which is just $1/4$ of the gluon condensate.

There are experimental indications that vector meson masses do undergo Brown-Rho scaling in medium. It has been shown by Shuryak and Brown [8]that the results of the STAR detector at RHIC demonstrated that the ρ meson mass was somewhat decreased at low density at RHIC and a recent CBELSA/TABS collaboration experiment[9] unambiguously showed that the mass of the ω meson while inside a tin nucleus is also less than in free space. Both decreases follow the quantitative estimates of Brown and Rho with Nambu scaling, corresponding to an $\sim 20\%$ drop in mass by nuclear matter density.

Meson masses are zero at T_c — It was argued by Brown et al. [10] that mesons whose masses decrease with temperature to zero at T_c could describe the large entropy increase found in lattice gauge calculations as $T \to T_c$. (Massless mesons give a greater entropy than massive ones.) In other words, the phase transition was described as mesons going massless, that is, chirally restored. The spontaneous breaking of chiral symmetry which gives the mesons their scalar masses is restored at T_c. It is plausible that the multiplet structure at $T_c - \epsilon$ reflects Weinberg's "mended symmetry" [11].

Thermal masses.— One of the surprises of the Bielefeld lattice gauge calculations was that they found the quarks to have very large thermal masses, of the order of $m_q \sim 1\,GeV$ at $T = 1.5\,T_c$ and similarly large masses at nearby temperatures. These thermal masses arise from the self-energy diagrams at finite T and, in our scenario, are the only masses just above T_c. It should be stressed that they are *not* scalar masses which break chiral symmetry but energies, that is, fourth components of four vectors. It has not been possible to calculate these masses analytically since the interactions just above T_c are supposed to be strong and hence nonperturbative. Weldon [12] obtained in perturbation theory a somewhat complicated formula involving momentum for the dispersion relation which could however be approximated to within $\sim 10\,\%$ by $p_0^2 \approx m_q^2 + \vec{p}^2$ with m_q a temperature dependent quantity which could be used as an effective mass in a simple hydrogenic model derived from Bethe-Salpeter equation as done in [13] following the argument of Hund and Pilkhun [14]. Remarkably, despite the presence of the effective mass, the helicity remains conserved as the quark wave function satisfies a free Dirac equation. We shall assume that this result holds non-perturbatively with the masses given by the Bielefeld lattice calculations.

Now $T_c = 175\,MeV$ so that the Boltzmann factor for the quark $e^{-m_q/T}$ is tiny. Similar results were found for gluons. Thus, there are not enough quarks and gluons present to produce the pressure, etc. found in RHIC experiments. If the mesons π, σ, ρ, a_1 in $SU(4)$ multiplets go massless at T_c, they can furnish the pressure. But they can only go massless if the binding of $\sim 1\,GeV$ quarks and antiquarks is $\sim 2\,GeV$, so the bound states have to be small, $\sim \hbar/(2\,GeV)$ in radius, much smaller than the typical $\hbar/(mc)$ of the usual mesons, where m is their mass. The calculation in [13] (described below) found the rms radius of the bound states just above T_c to be $\lesssim 0.4$ fm. The pion is an exception to this. The interaction must bring $2m_q \sim 2\,GeV$ to zero, and therefore is very strong.

The Bielefeld group [15] have carried out lattice gauge calculations to obtain the heavy quark free energy and entropy for the region of temperatures above T_c. Their results (for pure gauge) were used by Park, Lee and Brown [13] in agreement with their full QCD calculations [16] in almost all respects, once a rescaling by the relevant temperatures is made. From the energy and entropy the Coulomb potential V can be obtained

$$V(r,T) = F(r,T) - T\,\frac{\partial F(r,T)}{\partial T}\;. \tag{2}$$

We shall pay particular attention to $T \gtrsim T_c$, where we have $V(r)$, suppressing the T. The caveat here is that defining the thermal modification of a potential energy between the quark-antiquark pair is known to be complicated and subtle [17].

Now the calculations are for quarks of infinite mass. In order to use them for light quarks, which make up the $SU(4)$ multiplets π, σ, ρ, a_1 we must put in the magnetic (velocity dependent) additions. We will be guided by Brown [18] who considered the velocity dependence of the interaction between the two K-electrons in heavy atoms. In the case of Uranium, $Z\alpha \sim 2/3$ so we are not so far from the $\alpha_s \sim 1$ encountered here. Since the color singlet interaction is simply a Coulomb one, the difference from the Coulomb interaction in atomic physics being that since QCD is a gauge theory, it runs with scale, we can use the apparatus of high-Z atomic physics to put in the velocity dependence. A nice result of our procedure is that we obtain the correct number of degrees of freedom, that of 32 massless bosons as determined by LGS. The total interaction for stationary states is, translated to QCD,

$$V = -\frac{\alpha_s}{r}\,(1 - \vec{\alpha}_1 \cdot \vec{\alpha}_2)\;, \tag{3}$$

where $\vec{\alpha}_1$ and $\vec{\alpha}_2$ are the Dirac velocity operators. The $\vec{\alpha}$'s are also helicities, and have eigenvalues ± 1 above T_c. Thus, since the quark and antiquark move in opposite directions, $\vec{\alpha}_1 \cdot \vec{\alpha}_2 = -1$ and

$$V = -\frac{2\,\alpha_s}{r}\;. \tag{4}$$

These results follow because the quark and antiquark are in helicity eigenstates [12].

Lattice gauge calculations above T_c show collective excitations S, P, V and A, all degenerate [19]. These are just the Nambu-Jona-Lasinio collective states (collective because they are a sum over quarks and quark-holes) which continue on up through T_c [10].

In [13] the masses of the bound states (all 32 are degenerate) above T_c were calculated with input of the lattice results for the Coulomb potential [15, 16] with magnetic effects added. Since, the (thermal) quark masses m_q have not been calculated at T_c (only at $1.5T_c$ and $3T_c$) calculations were made for various assumptions within the range $1-2\,GeV$. It was found there that the meson masses go to zero at T_c regardless of this mass.

A simple hydrogenic model derived from Bethe-Salpeter equation [14] is invoked in [13] to show why the meson masses are zero at T_c irrespective of m_q. The resulting equation is essentially the Klein-Gordon one since the spin-dependent interactions can be neglected because of the large inertial parameter in the denominator of the magnetic moment as discussed below. It may very well be that this parameter goes to ∞ as T comes down to T_c from above as a result of confinement, making our approximation and the Weinberg mended symmetry [11] exact. In this model the heavy quark Coulomb potential is started from zero at $r = 0$ and increases to $2m_q$ (with string breaking ignored) at large distances. The chirally restored mesons would have energy $\sim m_q$ in this approximation (half of the absolute value of the $-2m_q$ potential energy). Introduction of the velocity-velocity interaction brings the meson masses to zero.

The chirally restored mesons have been found in quenched LGS at $T \approx 1.4T_c$ and $1.9T_c$ [19, 20]. In the heavy quark approximation Park *et al.* [13] deduced that the binding energy was $0.15\,GeV$ and the thermal mass $m_q \sim 1.2\,GeV$ at $1.4\,T_c$. Nonlinearities were not displayed; all 32 modes were degenerate. On the other hand, Brown *at el.* [21] found in the light quark formalism that just above T_c there were large nonlinearities. The width for $\rho \to \pi\pi$ was estimated as $380\,MeV$. (Above T_c this is the only interspecies transition, the π and σ and the ρ and a_1 being equivalent). Possibly the nonlinearities produced enough noise in the lattice calculations to prevent them from being extended below $1.4T_c$. (Difficulties did appear [22]). In any case the large $\Gamma(\rho \to \pi\pi)$ signals strong interspecies interactions.

Rescaling at T_c.— Just above T_c, the color singlet (Coulomb) potential predominates completely over the colored interactions. Thus only the colorless states matter. This can be understood roughly in the following way.

As long as hadrons with masses are present, chiral symmetry is broken and scales are set by the chiral symmetry breaking one $4\pi f_\pi \approx 1\,GeV$, where $f_\pi \approx 90\,MeV$ is the pion decay constant. However, once chiral symmetry is restored at T_c, the scale is determined by the π, σ, ρ, a_1 meson (scalar) masses which are zero at T_c. Suppose we

describe this effect – which is clearly absent in perturbation theory and hence highly non-perturbative – in terms of an *effective* Coulomb interaction with an "*effective* charge" that simulates movement towards the infrared, so that the "Coulomb interaction," evaluated in lattice gauge calculations of the Polyakov loop [15], becomes large, $\alpha_s \sim 2$. The effective coupling constant, with the $4/3$ value of the Casimir operator and the factor 2 for velocity dependence included, comes to $\alpha_s \to \sim 16/3$ as $T \to T_c$. Since $\alpha_s = g^2/4\pi$ this means that $g \to \sim 8$, and $g > 1$ being the strong coupling. This strong coupling is manifested in the interactions for $T \geq T_c$.

At first sight it may seem strange that the masses of the bound states which result from lattice calculations employing quite large bare (or current) quark masses $\bar{m}$ all drop so sharply toward zero. That explicit chiral symmetry breaking plays an insignificant role can be understood by realizing that in the presence of the explicit breaking, the total mass is

$$M = \sqrt{m_{th}^2 + \bar{m}^2} \approx m_{th} + \frac{\bar{m}^2}{2m_{th}} \qquad (5)$$

with $m_{th} \sim 1\,GeV$, so that $M \sim m_{th}$ unless extremely high $\bar{m}$'s are used in the LGS. Thus, the lattice calculations of the system entropy at T_c depends little on the explicit chiral symmetry breaking.

As the soft glue melts the interactions go to zero.— Let us now go up to T_c from below in the hadron sector. Since the hadronic interactions are given by the exchange of soft gluons, as these "melt" and disappear, the interactions go to zero. We have not yet rigorously established but we believe that the melting of the soft glue corresponds to the gauge coupling $g_V \to 0$, i.e., "the vector manifestation (VM)" in HLS theory [2]. In fact both the vector coupling constant g_V and the mass m_ρ go to zero at a fixed point at $T_c - \epsilon$. This gives rise to "hadronic freedom." This implies that as the fireball expands and T drops below T_c in heavy-ion processes, interactions between the hadrons cease, building up again as T drops to zero.

In going up to T_c from below, the dynamically generated masses of the mesons, such as the ρ, go to zero leaving only the bare mass $\bar{m} \sim 5\,MeV$. Since the width of the ρ goes as [21] $\frac{\Gamma_\rho^*}{\Gamma_\rho} \sim \left(\frac{m_\rho^*}{m_\rho}\right)^5$ replacing m_ρ^* by $5\,MeV$ one sees that the effects from the explicit chiral symmetry breaking are negligible. Thus, in conjunction with eq. (5), we see that the explicit chiral symmetry breaking changes the description of the chiral restoration transition only negligibly from that in the chiral limit; *i.e.* the effects from crossover, rather than second order phase transition would be difficult to see. We might have expected this from the fact that the behavior of the glue (see Fig.2 of [13]), which has no quarks in it, is a good guide to the chiral restoration transition.

We should note that whereas the VM with movement toward $g_V^* = 0$ at the fixed point brings the vector mesons to zero mass just below T_c and the symmetry determining

the zero mass of π and σ just above T_c is chiral symmetry (which protects the pion from mass), the apparent $SU(4)$ symmetry which seems to set m_ρ^* and $m_{a_1}^*$ equal to m_π just above T_c is not exact. The magnetic moments of quarks and antiquarks above T_c are given by eq. (21) of Brown *et al.* [23]

$$\mu_{q,\bar{q}} = \pm \frac{\sqrt{\alpha_s}}{p_0} \qquad (6)$$

where $p_0 = E - V$, and $-V \sim 2\,m_{th} \sim 2\,GeV$. The large inertial mass in the denominator of the spin dependence suppresses it greatly, but since the spin dependence is not zero, the $SU(4)$ symmetry is not exact.

Concluding Discussion.— Although our principal focus was on the vicinity of T_c, it is interesting to extend the scenario to higher T. The four detector groups conducting research at RHIC have announced that they have created a new form of matter, "the perfect liquid". The initial temperature at which RHIC matter is formed is $\sim 2T_c$. This liquid follows from the scenario of Shuryak and Zahed [24] which can easily be understood from the results of [13]. Namely, the thermal masses, divided by T, decrease toward the perturbative value

$$\frac{m_{th}}{T} = \frac{g}{\sqrt{6}}\,, \qquad (7)$$

so that the $q\bar{q}$-pairs will become unbound at $T \sim 2T_c$. As they unbind their scattering amplitudes become very large in magnitude, going through $\pm\infty$, so that the quark and antiquark mean free paths are small, giving the low viscosity of the perfect liquid.

Now there can be myriads of other states, both colored and colorless, which contribute substantially to the pressure as T increases to $\gtrsim 1.2 - 1.3\,T_c$ [24]. Admixture with these states will broaden the colorless modes we considered above, spreading the width but leaving the total strength of our colorless collective modes intact. These can be seen in the heavy quark calculations of Asakawa

et al. [19] as broad peaks of widths $\sim 3\,GeV$ at energy $\sim 4\,GeV$ for $T \approx 1.9T_c$.

From the perfect liquid as temperature drops the system goes into that of colorless bound states as we have outlined. Near T_c, colored objects are too massive to figure in thermodynamics. Then, as T drops through T_c, a complete "hadronic freedom" sets in as the interactions between mesons (other than pions) vanish. Later the on-shell hadrons get their interactions back.

Although there is evidence that the vector-meson mass drops in density [8, 9], the consequence of VM on which our principal thesis is based will be the cleanest near the critical point in that while the mass drops to zero, the width is to vanish more rapidly. Lattice measurement should be able to verify or falsify this prediction. Theoretical issues that need to be studied are the effect of quark masses ignored in the RGE flow to the VM fixed point and the mechanism as to how the same massless mesons go across between $T_c \pm \epsilon$. The latter may be addressed by holographic dual QCD once one knows how to calculate corrections to the large 't Hooft limit.

• **Note added**

After the paper was accepted for publication, it was brought to our attention that we had inadvertently left out an important paper that appeared in the same year as that of Ref.[4] by Su Houng Lee [25] who suggested the notion of two glues exploited in our paper and discussed also the possibility of nonperturbative quark-gluon dynamics being operative above T_c.

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